A MODULAR APPROACH TO THE KORBA AQUIFER SEAWATER INTRUSION STUDY, 1, GIS FIELD DATA ANALYSIS

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ABSTRACT

Seawater intrusion is an important environmental problem in the coastal aquifers of many Mediterranean countries. In the 438 km^2 Korba aquifer in eastern Tunisia, a large increase in the number of pumping wells for irrigation purposes since the 1960s has resulted in a lowering to below sea level of the water table in several observation piezometers, and in a consequent deterioration of the water quality. Several remediation scenarios are being considered for this region, including rationalization and control of water pumping from the wells, artificial recharge of the aquifer and construction of small dams to serve as an alternative source of irrigation water. In order to investigate the impact of these measures on the aquifer water quality, a GIS-based modeling study is being undertaken. The available data set comprises a number of layers of geographical information, giving a complete hydrogeological characterization of the region, and time series of chemical and hydrologic variables acquired during several ground sampling campaigns performed in the last thirty years. The GIS is used to organize this heterogeneous data structure and to control the data flow through various phases of the work, i.e. the pre-processing of input data for the model, the interpretation of model outputs, and the calibration of the model itself. The GIS serves also as a support tool in the generation of the 3-D computational grid used in the numerical simulations. In addition to describing the data structure and the organization of the system, the paper illustrates also the implementation of a simple recharge optimization scenario.

INTRODUCTION

An accurate description of the spatial and temporal dynamics of seawater intrusion is of critical importance in the study of aquifers affected by this type of contamination. A distributed flow and transport model, supported by an adequate knowledge of aquifer characteristics, can be a valuable tool to corroborate and extrapolate the observations provided by monitoring networks. Most importantly, distributed models allow a detailed simulation of the evolution of the intrusion process under different conditions, and –thus– the evaluation of the effect of different proposed remediation strategies. However, the vast amount and the heterogeneity of the data required for a study on a real site poses on the

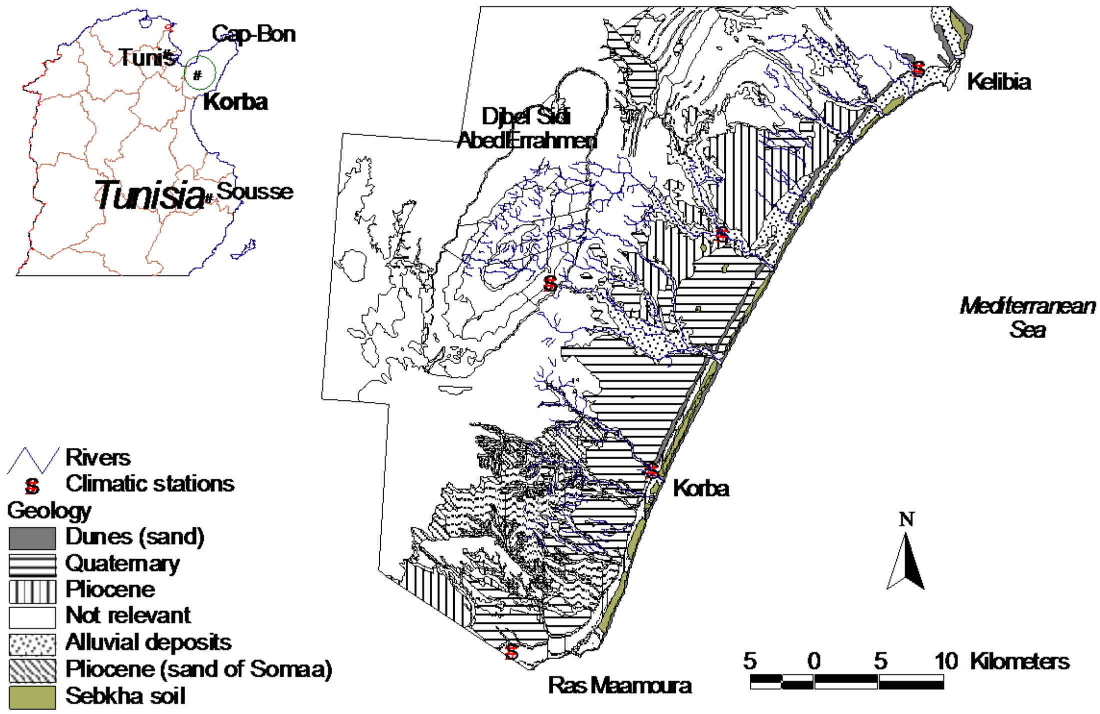

Figure 1. The Korba aquifer: location and simplified geologic map, indicating also the river network and the position of the climatic stations.

modeler a heavy burden, in terms of data processing and management, which is added to the actual modeling issues and which may greatly limit the modeling results.

Geographic information systems (GIS) have by now been well recognized as an ideal and almost indispensable support to environmental modeling (Hornberger and Boyer, 1995, Nyerges, 1993, Maidment, 1996). This is due to their capacity of handling georeferenced information and of offering the possibility of performing complex spatial analysis and visualization tasks within a consistent framework. Integrated applications of GIS and models may span from systems specifically dedicated to support the simulation process (Harris, 1993, Nachtnebel 1993), to complete implementations of decision support systems (Fuerst et al., 1993) for water resources management. However, GIS do have some limitations which require still additional tools for a comprehensive evaluation of the results of a complex groundwater model, such as the one adopted in this study. These tools typically include scientific visualization packages, for the intuitive representation of multi-dimensional data sets, and database management systems. The approach followed in the integration of such diverse tools represents a study topic *per se*, since the effort required by the integration process is significant and must be addressed by appropriate strategies (Paniconi *et al.*, 1998).

In this article, having given a description of the Korba site and of the data available for the study, we proceed to show how GIS has been used in the organization of the geographic data set. The analytic and graphic functionality of GIS, together with the customization capabilities offered by the available scripting languages have been exploited to develop a set of routines for the exchange of data with the numerical model, greatly simplifying and enhancing common tasks in the modeling process. These include the generation of the computational mesh, the definition of the boundary and initial conditions, and the visualization of simulation results. Finally, the possibility of exploiting the GIS/model framework for the analysis of remediation scenarios (which is the ultimate objective of this study) is briefly discussed.

DESCRIPTION OF THE STUDY SITE

The Korba aquifer is a part of the western coastal aquifer of the Cap Bon area, extending in the plain from the city of Ras Maamoura in the south to the city of Kelibia in the North, and is bounded by the Mediterranean Sea in the east and the Djbel Sidi AbedErrahmen anticline in the west. The aquifer covers an area of 438 km^2 and was formed during the Pliocene and Quaternary ages by sedimentation of eroded products from the Djbel Sidi AbedErrahmen anticline. The water table is located in the Plio-Quaternary formations and the aquifer substratum is constituted by underlying Miocene marl formations. Two distinct formations compose the Korba aquifer: a Pliocene sandstone whose stratigraphic series correspond to an alternation of sandstone and marl, and a Quaternary alluvium containing detrital sediment (sand, gravel, silt) with thin clay lenses. The sandstone formation spans the entire aquifer and has a mean depth of 85 m, while the detrital formation occurs in the south-western part of the aquifer and has a thickness that varies between 20 and 25 m. Aquifer depth is highly variable, ranging from 150 m in the south to 30 m in the north, and decreasing from east to west to nearly vanish at the Djbel Sidi AbedErrahmen anticline. A characteristic geomorphologic element in the area is the presence of a dune formation of quaternary sediments running parallel to the coastline and separating the Korba plain from the sea, characterized by a high hydraulic transmissivity.

The main hydrographic network consists of three rivers with irregular flow (*Owed*), which are completely dry in the summer. Precipitation on the Korba plain is monitored by five stations displaced in the area, and exhibits a very irregular and temporal distribution. According to the Korba station data, 60% of the annual rainfall is concentrated between November and March, and the rainfall deficit covers a period of nearly 10 months, reaching its maximum (150 mm) in July and August. Mean annual rainfall computed over an observation period of 28 years (1964 to 1996), is around 460 mm, and in exceptionally dry years rainfall may drop to one third of this value. The location of the Korba site and a representation of the described features are shown in Figure 1.

Natural recharge of the aquifer is insured by rainfall infiltration, for which an average of 32 mm/year has been estimated on the plain, with higher values in the river beds and in the dune areas, and lower values in the Quaternary areas. The Plio-quaternary aquifer receives its main natural recharge from the piedmont of Djebel Abderrahmane.

The Korba aquifer is exploited by 7309 wells extracting in all nearly 47×10^6 m^3 of water per year, against a permitted exploitation in the range of 50×10^6 m^3/year (Ennabli, 1977). The distribution of the wells is particularly dense towards the coastal part of the plain, determining a distribution of water exploitation which tends to accentuate the movement of the freshwater/saltwater interface.

Monitoring of the Korba aquifer was begun in 1962. The over-exploitation of the aquifer is reflected in a steady lowering of the piezometric level observed in the monitoring network (from 0 to –5 m) and in a consequent decrease in the yield of the pumping wells. At the same time, a continuous growth of water salinity has been observed in the eastern part of the site, with peak concentration values of 5 to 8 g/l.

AVAILABLE DATA

The data available for the study can be divided in three sets, respectively giving the hydrogeologic characterization of the site, the information on the exploitation of the aquifer, and the monitoring of the seawater intrusion effects.

Cartographic data are available for geology, hydraulic transmissivity, hydrography, topography and pedology. Together with a map of the aquifer limits obtained from a previous study (Ennabli, 1977) and information on the geometry of the base of the aquifer, these data are used to define the computational domain for the model and to provide a description of the physical properties of the aquifer.

The data on the exploitation of the aquifer is represented by a map indicating the position of clusters of wells (regularly distributed on the plain), to which values of exploitation are linked, repre-

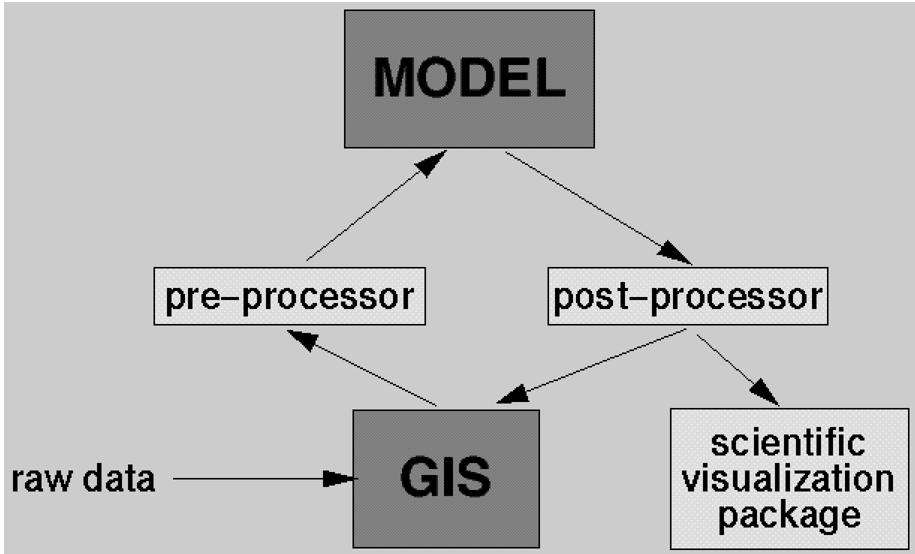

Figure 2. A diagram representing the flow of data through the components of the system.

senting the sum of the exploitation of the real wells. In addition, a map of the public irrigated zones is available, from which an indication on the eventual infiltration due to irrigation may be derived.

he third set of data concerns monitoring information. This is represented by a map giving the position of 99 monitoring wells located on the site. The monitoring well map is linked to records of piezometric level and various chemical parameters. Piezometry and salinity contour line maps derived from the monitoring data prior to this study are available, covering a significant part of the plain, for 1962, 1970, and 1996.

USE OF GIS IN THIS STUDY

Two main GIS-based tasks can be identified in this study: an initial editing phase, for the creation of the geographic data set from the available raw data, and an analysis phase, with a strong interaction between GIS and numerical model.

The ARC/INFO package has been used to digitize the geographic features from the source map sheets and to assign attribute information to the data layers created, while the interaction with the model takes advantage also of the graphical user interface provided by the ArcView package, and on a set of in-house developed FORTRAN 90 routines. The resulting data framework, illustrated in Figure 2, shows how the GIS and the model act as two loosely integrated units, connected through a layer represented by the pre- and post-processing modules.

Creation of the geographic data set

All geographic data used in this study was initially available in paper format, in different scales and deriving from different sources. The first step was to digitize from the cartographic media the required information, and –for each of the required themes– to join the data deriving from separate map sheets into layers covering the whole region. In this process several consistency issues had to be faced and solved (e.g. differing classifications for geologic map sheets dating back to different years). In general, the aim was to create a faithful replication of the original data set, from the point of view both of geometry and of attribute data.

The salinity and piezometry maps, as well as the transmissivity map –which were taken from previous studies on the site– did not contain any geographic coordinate reference, and thus needed to be georeferenced on the more reliable data layers, taking the control points from the coastline, which was the only recognizeable geographic feature. This map, in conjunction with the geologic map, was used to define the surface limits of the aquifer.

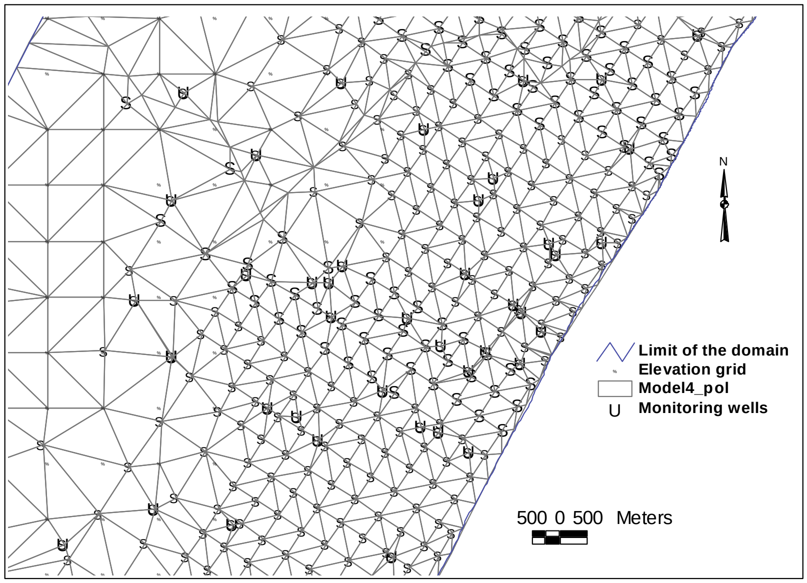

Figure 3. A detail of the 2D mesh created using ARC/INFO. The mesh configuration and resolution was in part determined bt the location of pumping and monitoring wells, which were made to coincide with grid points.

A 50x50 m digital elevation model for the study was obtained by interpolation of the topographic data.

2D mesh generation

The finite element mesh used by the CODESA-3D model (presented in part 2 of this paper) is derived from a 2D mesh generated using the module available in ARC/INFO for the creation of triangulated irregular networks, or TINs (Environmental Systems Research Institute, 1988). The advantage of this approach, compared to the use of other non GIS-based mesh generators, is that a direct link is maintained between the mesh structure and the (geographic data) input on which it is based. As a consequence, the user can benefit from a more intuitive identification of the important features, which may either be represented by the "primitive" data layers, or by the result of complex spatial analyses, combining different information.

The TIN data structure holds information on geometry (coordinates of all nodes, and connectivity, defining arcs and triangles), and on a parameter representing the *z* dimension (typically elevation), which is automatically interpolated at all nodes, given a set of points with assigned *z* and a description of existing discontinuities and "clip" areas (which can be used to exclude parts of the domain from the interpolation), thus allowing to incorporate the most diverse geometric features and to reproduce even very complex surfaces. All the information held in a TIN can be exported to a simple ASCII file format, which can easily be processed to obtain the input data for the model.

The main problem which has been encountered in this approach is that the TIN module provides only basic means to assess the quality of the resulting mesh with respect to regularity and associated numerical problems. In the case of an Eulerian model, and in order to eliminate numerical dispersion and instability, the mesh must satisfy the Péclet criterium (Huyakorn, 1984). Furthermore, an indirect influence on the conditioning may be given by the presence of patch elements, i.e. clusters of many elements connected at one node (Kunianski, 1993).

Since the GIS-supported mesh generation requires a fraction of the time compared to manual design or use of structural mesh generation packages, the strategy adopted in this study was to base the selection of the 2D mesh on an iterative process, with a first qualitative assessment of the TIN output, directly followed by simulation tests to highlight numerical problems, which were in turn used to modify the input for the mesh generation.

Even though the TIN module has a number of control parameters, which can be used to specify how nodes are to be extracted from each of the input data layers (and how the *z* values are to be interpolated), it has been observed that in the case of the elevation contour lines it was not possible to obtain a satisfactory distribution of nodes. It was then decided to derive the nodes from the raster DEM, imposing a sampling distance of 500 m. In addition to elevation, the features considered in the definition of the 2D mesh are: the pumping and monitoring wells, the limits of the computational domain (based on geologic outcrops), and a reclassified transmissivity map.

Once the 2D mesh is generated, the layer holding the aquifer depth information is automatically queried in correspondence of the element nodes, outputting the aquifer depth values necessary to define the 3D computational domain. The user is guided in this process by means of a routine developed in AML, the scripting language used by ARC/INFO, while the conversion from the TIN ASCII export format to the format required by the model is performed via a set of FORTRAN 90 routines.

Definition of boundary and initial conditions

In addition to defining the geometry of the 2D mesh, GIS functionality has been used to define the boundary and initial conditions for the simulations. Once the TIN has been created, its elements can be converted to geographic data coverages (either in point format, representing the nodes, or in polygon format, representing the triangles). The identifiers of the elements in these coverages are consistent with the identifiers of the TIN and of the 2D mesh. This allows to transfer physical parameters (or the result of any spatial processing on the available coverages) to the mesh. In this task the user takes full advantage of the graphical user interface provided by Arcview.

Support to analysis of simulation results

The output of a simulation is fed to a post-processing module composed of a second set of FORTRAN 90 routines and AMLs, converting the numerical results back to ARC/INFO TIN and coverage formats, which can be used to compare the results of different simulation runs and the data acquired from the monitoring network. In particular, piezometry contour lines are derived from the TINs for an immediate comparison with field data. Advanced three-dimensional visualization of the results is performed outside the GIS environment, employing a scientific visualization package, as presented in part 2 of this paper.

Analysis of remediation scenarios

Several remediation scenarios are being considered for the Korba region. These include rationalization and control of water pumping from the wells, artificial recharge of the aquifer, and construction of small dams to serve as an alternative source of irrigation water. The evaluation of these scenarios requires a combined use of the spatial analysis capabilities offered by the GIS and of the simulation model.

The criteria defining optimal remediation strategies can be applied to the site by means of GIS-based spatial analysis functions and algorithms. For instance, it may be possible to define the position of one or more reservoirs, minimizing the cost of water distribution and maximizing the extent of the areas which can be subject to recharge with their supply. The scenario thus identified then needs to be translated into an appropriate set of boundary conditions for the numerical model and –finally– results from the simulation can be brought back to the GIS, to be analyzed and compared with other scenarios.

In the framework of this study it has not been possible to undertake an exhaustive analysis of different scenarios or to implement sophisticated multi-criteria methodologies, and only a preliminary test has been performed. This takes into account the geomorphology of the site, and iden-

Figure 4. Result from a preliminary recharge analysis, undertaken for the central part of the Korba site. A lighter tone indicates a higher suitability for artificial recharge. The dots represent the pumping wells located in areas of high suitability. The outermost lines indicate the limits of the computational domain.

tifies areas characterized by a higher suitability for artificial recharge, estimated as a function of hydraulic transmissivity, geology, and local slope. To this end, the corresponding geographic data layers have been reclassified, passing from the value of the initial parameter to a qualitative index representing the suitability; the three indices have then been summed, leading to the final estimate (Figure 4). The pumping wells corresponding to the high suitability areas can be automatically identified and the appropriate boundary conditions for the model are assigned.

CONCLUSIONS

The possibility of supporting a distributed model with a robust geographic information system, consisting of a well-designed geographic information data set and of software facilities that provide a seamless data exchange between the GIS, the model, and the visualization packages, greatly enhances any environmental modeling study. The most substantial benefits of a GIS support to the model may be summarized in the possibility of manipulating data in an extremely direct and intuitive manner (i.e. the modeler can think in terms of physical features), leaving to the data infrastructure the burden of transforming the results of his spatial analyses in the form required by the model. In addition, heavy tasks – such as mesh generation or assignment of complex boundary conditions– can be automated and performed in a fraction of the time usually needed in absence of a GIS support. On the other hand, even though the trend is towards a growing integration between different GIS and models, the effort required to set up a an integrated framework remains very consistent.

The production of the geographic data set for the Korba aquifer, in addition to providing the data source for the numerical model, represents *per se* an important outcome of this study, since it has allowed the merging of a vast amount of information, collected from diverse sources and over many years and thus characterized by inconsistencies which could have been untreatable without an adequate GIS platform for data management.

The analysis of alternative remediation scenarios for the Korba site needs to be carefully addressed, and only preliminary tests have been undertaken in this study. In addition to a more comprehensive data set including information on data uncertainties, gaps, and errors, it should be noted that a robust remediation analysis also requires a properly calibrated model.

ACKNOWLEDGEMENTS

This work has been supported by the European Commission through grant number AVI-CT93-2-073 and by the Sardinia Regional Authorities.

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